THE ORIGIN OF THE LUNAR FORMATIONS

By William H. Pickering.

Owing to the great number of craters scattered over the surface, the brighter portions of the Moon present a strikingly different appearance from the terrestrial landscape, and various theories have been offered to account for this fact. The darker regions, on the other hand, which form about one-half of the total visible surface, differ much less from the terrestrial continental areas.

The larger lunar craters may be divided into two classes, those with smooth floors like Plato and Ptolemaus, and those with rough and irregular ones like Copernicus and Tycho. This difference is well illustrated in a photograph taken at the Mount Wilson Observatory and published in *Popular Astronomy* for December. The craters Stöfler and Albategnius, altho near the terminator, are seen to have perfectly smooth floors, while those of Tycho and Alphonsus are rough. In the case of the former class the floors are frequently dark like the *maria*, in the case of the latter they are bright and often furnished with a central peak. It is only reasonable to believe that these two classes were formed in the same way, and that the floors of all were originally rough and of the same color as their walls. The modification which subsequently produced the smooth floors appears to have been a welling up of dark colored lava from beneath, like that which produced the *maria*. This lava melted the original floor and central cone, and combined with them. In some regions, such as the western portions of Imbrium and Serenitatis, and the south of Nectaris and Procellarum, the crater rims themselves were partially dissolved in the melted surface of the *mare*. It is clear from this fact that a very large proportion of the lunar surface was at one time or another liquid.

What appears to have happened is this. When the Moon first began to cool, the material of lighter color and lighter specific gravity solidified on the surface. A thin surface shell favors large craters, but there is no evidence that any of these were of an explosive character. When the shell became thicker, and communication with the hot interior more difficult, the craters formed became smaller, and impinged on the larger earlier ones. When the shell contracted by cooling and solidification, the hot

molten interior broke thru the surface, in much the same way as now happens on a small scale in Kilauea, Hawaii.

The various *maria* were formed at this period, and about half of the original crust was thus destroyed and dissolved. Had the Moon been much smaller, its surface area would have been larger in proportion to its fluid contents, and a smaller fraction of the surface, or perhaps none at all, would have been destroyed. On the other hand, had the Moon been much larger, the whole of its original surface might have vanished, piece by piece. This is probably what actually happened in the case of the Earth—our larger early craters have all been dissolved one after another, as the result of successive contractions and eruptions, in the igneous rock with which the whole surface was formerly covered.

Our terrestrial craters must therefore be compared, not with the great craters of the white areas of the primitive lunar surface, but rather with the smaller dark ones of the lunar *maria*. Much the largest of these dark craters is Marius, 27 miles in diameter, and situated on the Oceanus Procellarum. The next largest is Reiner, 21 miles in diameter, and located near it. Perhaps the size of the *mare* affects the size of the crater, for those that are next largest are well scattered over the lunar surface. Half a dozen of them, such as Arago, Lambert, Ross, Deslisle and Torricelli, range from 18 to 15 miles, and from that they go down, increasing rapidly in numbers, to the smallest size visible. The three largest terrestrial craters, according to Gilbert, are located in the Philippines, in Japan, and in Kamchatka, and their diameters each measure about 15 miles. Indeed in northern Japan there is a deep circular bay some thirty-five miles in diameter, surrounded by volcanic peaks, two of which are still active. It is known as Volcano Bay, and is clearly an extinct crater, perhaps the largest in the world. It clearly resembles Fracastorius on the Moon. Since our largest craters were necessarily among our earliest, many of them must have succumbed to long continued erosion, and other atmospheric influences, which would not have affected the lunar ones. It therefore appears that the really comparable terrestrial and lunar craters are all of about the same size.

If we compare the lunar *maria* with the similar, somewhat elliptical terrestrial volcanic areas, such as the Caribbean Sea, or the five great seas that bound the coast of Asia on the east, extend-

ing from Behring's Strait to the Strait of Malacca, we cannot but be struck with the very small comparative size of the lunar formations. Thus the smallest of these six terrestrial seas, that of Japan, is of practically the same size as the Mare Imbrium.

It is frequently suggested that the lunar *maria* were formerly covered with water, in fact are old sea bottoms. There is no adequate evidence in favor of this suggestion to be found upon the Moon at the present time; in fact all the evidence available is directly against it. The lunar atmosphere, on account of the gravitative constant, can never have been very dense like our own, and the rapid evaporation from extensive lunar oceans under low pressure, and exposed to the tropical rays of the Sun, would have produced deeply eroded valleys and extensive river systems, which are conspicuous on the Moon only by their absence. It is true that very small eroded valleys do exist, also small river beds, the largest of the latter, measuring around the curves, being some sixty-five miles in length. The tapering forms of these last, however, show that their source was in each case a small craterlet in which they terminate, and that the water continuously evaporated as it flowed from it to the lower levels. There is no evidence of great river basins such as are found upon our Earth.

Moreover, the *maria*, altho frequently in communication, are often situated at different levels, as can be seen under a low Sun. Their centers are also higher than their edges. As the water gradually dried up, and the upper areas emptied into the lower ones, distinct channels should have been cut connecting them. Nothing of this sort is to be found upon the Moon, and the *maria* when well seen present precisely the appearance of gigantic lava fields with occasionally wrinkled surfaces, such as must formerly have existed upon the Earth in India and Idaho, and are now seen on a small scale in many terrestrial craters. In order to form a scale of comparison, it may be stated that the lava fields of India are about equal in area to the maria Serenitatis and Tranquillitatis combined.

No evidence of explosive volcanic action of the Vesuvian type has been found anywhere upon the Moon, with the possible exception of the construction of the central peaks of some of the older formations. Vesuvius is itself a central peak, of the extinct Monte Somma. Teneriffe is similar. In both these cases the central peak is much more prominent than the original crater.

On the other hand, in the case of Pico in the Azores, rising to an altitude of 7600 feet, the peak is comparatively insignificant. It rises to an elevation of only 350 feet above the crater floor at its base. The diameter of this outer crater is about one-third of a mile, and thirty feet below the summit of the steep central cone, a little craterlet some fifty feet in diameter was found, still exhaling steam in the summer of 1907. The temperature within the vent was 147°F.

Across the crater floor from the peak to the edge extends a volcanic crack or rill, much like that to be seen in Petavius. Half a dozen little irregular craterlets are scattered along its length, the largest being about thirty feet in diameter. In the earlier days of its eruption the crater was evidently of the explosive type, as is indicated by the loose scoria scattered about its base, but the floor of the crater is solid lava, showing that in its later eruptions it more closely resembled the lunar volcanoes. In the volcanoes of Hawaii, which also resemble those of the Moon, central peaks rarely if ever occur, but little craterlets scattered irregularly over the crater floors are a common occurrence. Indeed, nearly all of the characteristic lunar features are to be found in one or the other of these two groups of islands. (See *Appalachia*, **11**, 344, 1908, *Memoirs American Academy*, **13**, 151, 1906.)

On the other hand, lunar volcanoes distinctly resembling terrestrial ones have also been found. There is one lying between Kies and Mercator whose cone measures 2000 feet in altitude and nine miles across at the base. The summit crater is about 4000 feet in diameter. The mean angle of the outer slope is 4°.8. It is even flatter, therefore, than Mauna Loa, whose slope measures 5°.1. It is illustrated in Figure 6 of the above mentioned *Memoirs*. Many other similar volcanic cones, scattered over the lunar surface, are now known. One with a crater 9,000 feet in diameter lies on a long ridge 130 miles east of Lalande, still another south of Mairan, and another south of Herodotus, and eight between Copernicus and Kepler. A group is suspected northwest of Marius.

At different times various curious theories have been suggested to explain the lunar craters, the chief stumbling block in the way of the volcanic theory, apparently, to their authors, being the great size of the lunar craters as compared with that in Vesuvius. Most of these theories were promulgated before the larger craters about the Pacific were generally known. An early idea was that the

lunar craters were the scars left by gigantic bubbles. In volcanic regions where the lava is very viscous, great bubbles several feet in diameter are sometimes formed. The writer, accompanied by several friends, has been inside of such a bubble, left on the lava fields of Arizona. Bubbles one hundred miles in diameter, however, do not seem likely to have occurred, even on the Moon.

Another theory advocated many years ago by Mr. S. E. Peal was that the site of each crater was formerly occupied by a pool of water. As the water evaporated it was deposited as snow in the region immediately surrounding it, thus building up the crater walls. Since the craters must be very ancient, however, their walls in that case would long ago have flattened out in the process of melting and of glacial flow.

Still a third theory, which has recently been revived from obscurity by the great war was first proposed by Proctor in 1873, "The Moon," p. 346. This suggests that the lunar craters are the holes left by great meteors that fell into them in past ages. A crater probably formed in this manner actually exists upon the Earth in Arizona, and possibly a second smaller one has been found. But why there are not more of them, or at least some evidence of their remains, since the Earth is so much more massive than the Moon, has not been explained. It will be noted that the Arizona crater has no central peak. The most popular idea among the adherents of this theory is that these gigantic meteors were revolving around the Sun with planetary speed, but have since disappeared. To this suggestion is raised objection (*a*) that the lunar craters are nearly circular, whereas on the meteoric theory they should in the great majority of cases be ellipses with a marked east and west elongation. To meet this objection it was proposed that the meteors revolved not about the Sun, but about the Earth in a ring, and simply dropped into the Moon by their own gravity, since their orbital speed would be nearly the same as that of the Moon.

To this has been raised objection (*b*) that with only two insignificant exceptions out of several hundreds of cases, among all the lunar craters, the smaller craters impinge on the larger, as they should do if they were of volcanic origin, whereas if caused by meteors, a large proportion of the smaller meteors would fall early, and their craters would be impinged on by larger ones.

Shell craters formed by exploding projectiles were a universal feature of the late war. Smaller craters, but more nearly analogous to the lunar ones, have been formed artificially by drops of water falling on a layer of thin mud, by firing pistol bullets into hardening plaster of paris, and by projecting clay balls against a soft clay surface. By these means even the central peak is occasionally produced by the reaction from the elevation of the crater walls. It is very doubtful, however, if this would occur in a larger formation, and, as we have seen, there is no evidence of it in the case of the Arizona crater.

Craters formed by the projection of clay balls, by solidifying paraffin, where the lower liquid layers are caused alternately to rise and fall as by tidal action, thru holes in the upper solid crust, and a crater formed by natural processes in iron slag are all illustrated in the writer's book "The Moon," Plate A. In the craters produced by projectiles it will be noticed that the outer walls are steep or perpendicular, while the inner walls are shelving. This is the reverse of what we find on the Moon, and may be called objection (*c*). In the craters formed by solidfying paraffin and slag, on the contrary, the inner walls are steep and the outer ones shelving, as on the Moon.

Objection (*d*) to the projectile theory lies in the difficulty of explaining the terraced interior walls of some of the craters, such as Tycho and Moretus, excellent photographs of which by Pease were published in the December number of this periodical.[1] Tidal action on a liquid floor, which solidified before the central peak was formed, would produce just such an effect. The crater Wargentin, in which the sublunar vent became plugged while the floor was at high tide, filling the crater walls to the brim, is a striking example of a phenomenon that may easily be explained by combined tidal and volcanic action, but is very difficult to explain as being caused by a projectile. Wargentin is fifty-four miles in diameter, and rises 1500 feet above the outer plain. It was generally supposed to be unique upon the Moon, but a similar much lower crater, fifteen miles in diameter, lying two diameters southwest of Bullialdus was discovered some years ago, and is described on page 161, and represented in Figure 32, in the *Memoirs of the American Academy* above mentioned.

[1]It is be to noted that both of these photographs are turned right for left, having been taken with a reflector, and not having been reversed in the enlargement. In the first, the lettering of the orientation is wrong, and an E should be substituted for the W.

A final objection (*e*) may be made to the projectile theory, in that it does not explain the fact that many of the central peaks of the larger craters exhibit small craterlets on their very summits. The exact centering of these craterlets cannot be the result of accident, and while most of them are small like Vesuvius, yet some are large enough to be readily seen in northern climates, even with small apertures. This is precisely the phenomenon we should expect to find if the craters were due to volcanic action. During the past two or three months an occasional search has been made for such summit craterlets, and as a result Table I has been prepared. It is clear from this that but few of the craterlets are larger than that in Vesuvius. The successive columns give the name of the crater, the diameter of the craterlet in feet, the colongitude at which it may be observed to advantage, and the type of central peak on which it is found. The diameters were determined by means of a Scale of Lakes attached to the telescope, such as is used for measuring the size of the lakes on *Mars*, and is described in full in the Report on Mars No. 7, *Popular Astronomy*, **22**, 617, 1914.

TABLE I

Name	Diam.	Colong	Type	Name	Diam.	Colong	Type
Timocharis	11,500	40°	*a*	Albategnius	3,500	20°	*c*
Plinius	9,500	0°	*a*	Alpetragius	3,500	30°	*a*
Herschel	9,500	30°	*b*	Pitatus	3,500	40°	*a*
Landsberg	6,000	50°	*c*	Piccolomini	3,000	350°	*d*
Capella	5,000	350°	*a*	Arzachel	3,000	30°	*b*
Burg	4,000	0°	*b*	Kant	2,500	0°	*b*

The central peaks have been divided into five classes according to the amount of erosion that they exhibit. Those showing little or none, like Alpetragius are classed as *a*. Those where the destruction exceeds one-half the volume of the original cone, and where it is therefore divided into several separate peaks, as in Copernicus, are classed under *e*. (*Popular Astronomy*, **24**, 441, 1916). Where the destruction is great, it will be seen by the table that the summit craters are not generally visible.

In some cases, however, where no crater has been found, even after careful search, we still find evidence of its existence. Thus in the case of Theophilus, whose central cone is deeply eroded, and is in class *d*, we find that the highest of the peaks is only moderately

bright, 8, at sunrise, and all the others dark. As the lunar day progresses the peak brightens, and one terrestrial day before lunar noon a minute brilliant point about half a mile in diameter appears on its highest summit. In the next four days four other brilliant points appear on lower summits. After three or four days they all fade away, and before lunar sunset only a few light hazy areas remain. The succession of phenomena is not always identical at different lunations. (*Popular Astronomy*, **25**, 149, 1917.) We can hardly doubt that we have here the clue to the erosion of the central peaks, and that the brilliant points shown indicate the location of invisible craterlets, emitting not ashes or lava, but steam, which immediately condenses to cloud and snow. The deep U-shaped ravines cut in these peaks indicate that in former times the amount of moisture was far greater than at present.

In the case of Kant, included in Table I, the central peak is first clearly seen at co-longitude 347°. It is then sharply defined, and remains so until 20°, but by 35° is distinctly hazy as compared with detail on the crater floor, and the eastern rim. The western rim contains two minute craterlets, and like the peak is now also hazy. This rim and the peak both brighten as lunar noon approaches, the latter reaching 9 and the former 8. By 128° all haziness has vanished, and the craterlet on the central peak appears distinctly surrounded by snow. To detect this the quality of the seeing should be at least 9 on the Standard Scale. The observation was made with an 11-inch aperture and a magnification of 430. It should be noted that a lunar eruption lasting for eight terrestrial days is exceptionally long. Two or three days is the usual limit.

We may indeed say that the arguments of greatest consequence, in favor of meteoric action upon the Moon, lie not in the craters at all, which are generally circular or polygonal, excepting at the two poles, where they have a tendency to be square, but rather in certain long and straight valleys, some of which are fairly conspicuous upon the lunar surface. This view has recently been argued and supported at some length in the *Journal of the British Astronomical Association*, by several writers. Even here, however, the evidence under favorable definition is distinctly against a meteoric origin. The largest of these valleys, located near Rheita, is composed of eight craters in its broader portion, and five where it is more narrow. They are in close contact, and have evidently

been exposed to pressure and torsion while in a heated condition, so that they appear a little like a short section of rope.

More than a dozen valleys of various lengths and breadths, and all nearly parallel, are located in the bright portion of the Moon near the center of the disk. The most western of these, some six diameters south of Menelaus is obviously composed of six craters in line, the southern ones being not so clearly marked as those at the northern end. The ruins of transverse crater walls crossing the valleys are seen in some cases. In others the grooves are partly filled with lava, formerly melted, thus concealing their floors and their origin. In the case of Hipparchus there are three short grooves nearly in line, two on the rim, and one between them on the floor. The northern one is the wider, but this is the only case where there is any appearance of the grooves cutting the ridges and skipping the hollows, such as a swiftly moving meteor might do. Immediately west of Albategnius is a longer groove which clearly follows the surface up and down hill. In no case is there any evidence of a meteoric body at the end of the groove. The sides of these grooves are elevated like crater walls, and are sometimes sinuous where different craters have joined one another.

Two and five diameters west of Apianus are two small grooved valleys, composed respectively of five and seven craterlets, which are intermediate in structure between the larger ones that we have been discussing, and an ordinary crater rill. One diameter west of Posidonius is a winding rill of the ordinary type at the north and south, but wider in the middle section, and analogous to the grooved valleys in appearance. There can be no question but that all of these valleys are due simply to confluent craters which have sprung up along the line of a submerged volcanic crack.

There remains one other lunar marking, and one only, which has been sometimes suggested as due to a gigantic meteorite, or the nucleus of a comet. This is the Valley of the Alps. It is 95 miles long, and at a maximum six miles wide. Except where crossing the Alps themselves it is a thousand feet deep. It connects the Mare Frigoris with Imbrium by a continuous, flat, nearly straight channel. Comparing it with terrestrial formations, we find that it is one-fifteenth of the length of the Red Sea, one-thirtieth its breadth, and one-fifth of its depth. It shows no evidence of a crater, nor of the ploughing up of rocks by a giant projectile. It certainly is not a crater valley. It appears to be

simply a crack across the narrow strip of the original surface crust separating the two maria, and was partly filled, and perhaps enlarged, by liquid lava from beneath. During a favorable libration the whole length of its floor can be seen from end to end, with the exception of a very short section hidden behind the volcanic peak Mont Blanc δ. This peak contains two minute summit craters each 3000 feet in diameter. The floor of the valley contains a string of somewhat larger craters, which are just visible, or partly visible, when favorably situated, over the southern edge of the floor, in the widest portion of the valley. Beyond them a narrow rill extends along the middle of the floor. It was first described in *H. A.* **32**, 84, and was subsequently independently discovered by Perrine, who gives a careful drawing of it in these PUBLICATIONS, 1904. It should be looked for between co-longitudes 0° and 60° and is most easily seen in front of a diamond-shaped marking where the valley first enters the Alps. The valley then narrows and again widens for a short distance. Here the rill as it crosses the center of the floor is really a delicate test object, but can be held with seeing 10, and a power of 430. It can hardly be over 500 feet in width at this point, and is perhaps not over two hundred.

In conclusion we may say that as far as our investigations go, it appears not only that the great craters which the meteoric theory was invoked to explain are not caused by meteors, but that none of the other markings supposed to be so caused show any evidence whatever of having a meteoric origin.

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